Forage Subsurface Drip Irrigation Using Treated Swine Wastewater

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Abstract. *The rapid expansion of animal production in the eastern U.S. in the 1990s resulted in large quantities of concentrated animal waste that must be utilized or disposed of in an efficient and environmentally friendly manner. To address these environmental concerns for wastewater utilization, we installed a subsurface drip irrigation system to apply treated swine wastewater effluent for bermudagrass hay production. The overall study objective was to determine the feasibility of using subsurface drip irrigation (SDI) for treated wastewater effluent applications. The specific objectives for the SDI system were to compare bermudagrass hay production using (1) commercial and wastewater effluent for nutrients, (2) two SDI lateral spacings (0.6 and 1.2 m) installed at 0.3 m below the surface, and (3) two irrigation application rates based on calculated evapotranspiration (ET_c) requirements (75% or 100%). The two-year study measured hay yields, hay biomass, soil nutrients, and soil water nutrients. The SDI system was successfully operated for two years applying effluent and commercial fertilizer to supply the nutrient requirements of the bermudagrass hay. Bermudagrass hay production for 2004 and 2005 ranged from 5.65 to 14 Mg ha^{-1}. Results from the SDI system indicated no significant differences between the SDI lateral spacings or irrigation application rates. Treatments using wastewater effluent had significantly higher hay yields and significantly higher nutrient biomass removal rates than the commercial fertilizer treatments. Nitrate-N observed in soil water lysimeters increased with depth, indicating the potential for leaching without proper management. Soil nitrogen and carbon were not significantly different for any of the treatments but did vary slightly over the life of the project.*

Keywords. *Bermudagrass hay, Forage, Irrigation, Land application, Subsurface drip irrigation, Swine waste, Treated effluent.*

In the eastern U.S. during the early 1990s, animal production expanded rapidly. In North Carolina, the number of swine increased from approximately 2.8 million in 1990 to more than 9 million by 1996 (USDA-NASS, 2006). This rapid expansion of animal production has resulted in greater amounts of concentrated animal waste that must be utilized or disposed in an efficient and environmentally friendly manner. This rapid expansion has exceeded the pace at which new innovative treatment systems have been developed. The animal production industry has been aggressively investigating and adapting new alternative wastewater treatment technologies. Additionally, the expansion of animal production has led to fewer, more concentrated operations that are challenged to treat, utilize, and/or dispose of the waste in an environmentally friendly manner. Additional challenges and concerns from these operations are odors, ammonia emissions, and pathogens. Many new and innovative systems still rely on land application of treated wastewater that typically use high-volume sprinkler irrigation systems.

The environmental impact of applying swine lagoon effluent and utilizing the nutrients for forage production has been extensively studied. Burns et al. (1985) investigated the effects of swine lagoon effluent applied to coastal bermudagrass with sprinkler irrigation using nitrogen loading rates from 335 to 1340 kg ha^{-1}. They found increased production and increased forage nutrient content with increasing nitrogen application rates. At the higher nitrogen application rates, they concluded that large quantities of applied nutrients were not recovered in the forage and thus would be lost to the environment. In companion studies, King et al. (1985) and Westerman et al. (1985) investigated impacts of the effluent applications on soils and runoff. King et al. (1985) found increasing soil nitrate levels with increasing application rates. Westerman et al. (1985) found low runoff potential during the waste application season and that the greatest potential for nutrients loss was movement into the shallow ground water. At the same study site, Evans et al. (1984) found increased nitrate in the ground water from subsurface drainage.

Adeli and Varco (2001) investigated the use of swine lagoon effluent as a source of nitrogen and phosphorus for forage grasses in Mississippi. They found increasing yields with increased nitrogen application for both effluent and conventional fertilizers. Higher nitrogen loading rates increased the residual soil nitrate-N concentrations. Liu et al. (1998) found increased buildup of soil nitrate with an increasing load

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(560 to 2240 kg N ha^{-1}) of both swine lagoon effluent and ammonium nitrate. They also reported an increase in soil phosphorus with the increasing swine lagoon effluent application rates.

Subsurface drip irrigation (SDI) systems can help address some concerns about land application of treated animal effluent. The SDI systems apply effluent below the soil surface and can eliminate spray and drift from land application, thereby reducing odors and ammonia volatilization. The SDI systems may also be used during periods of high wind or low temperatures, when sprinkler application would not be acceptable.

Suarez-Rey et al. (2000) compared sprinkler and subsurface drip irrigated bermudagrass turf with reclaimed water in Arizona. They found no significant differences among the irrigation system, turf growth, appearance, or soil electroconductivity. Norum et al. (2001) investigated the use of subsurface drip irrigation to apply dairy effluent to forage crops in California. After initial filtrations problems with the effluent, they produced alfalfa forage yields similar to commercial growers. Subsurface drip irrigation systems have been used in Kansas to apply beef lagoon effluent with successful results (Lamm et al., 2002).

In the southeastern Coastal Plains, little research has been conducted using SDI systems for wastewater application. Subsurface drip irrigation systems may offer an alternative to traditional overhead sprinkler application. The SDI systems could also help reduce ammonia emissions and odors associated with sprinkler applications. The overall objective for this study was to determine the feasibility of using SDI for effluent application. The specific objectives for the SDI system were to compare bermudagrass hay production (1) using commercial and wastewater effluent as nutrient sources through the SDI system, (2) using two different SDI lateral spacings, and (3) using two irrigation application rates based on calculated crop water requirements. An additional objective was to evaluate the system impacts on soil and water quality.

Table 1. Typical treated effluent characteristics (Vanotti, 2004).

Water Quality Parameter	Raw Flushed Manure (mg L^{-1})	Treated Effluent (mg L^{-1})
pH	7.6	10.5
TSS	11,051	264
BOD_5	3,132	10
COD	16,138	445
Soluble P	135	8
TP	576	29
TKN	1,584	23
NH_4-N	872	11
NO_3-N+NO_2-N	1	224

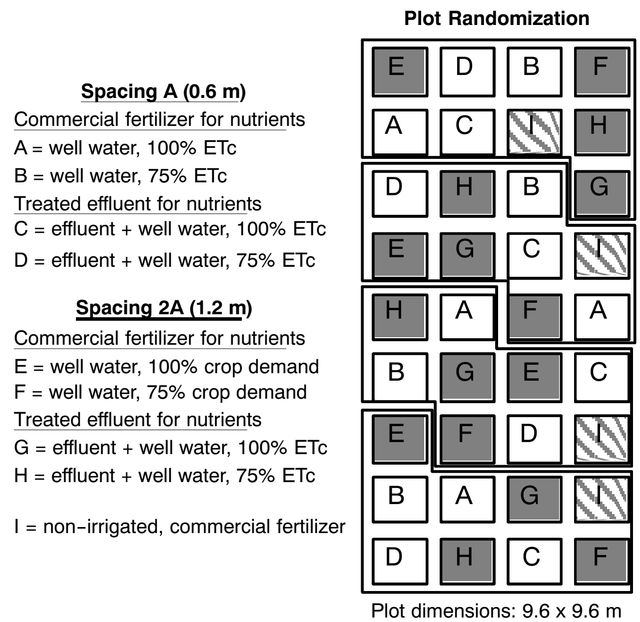

Figure 1. Plot plan for the subsurface drip irrigation bermudagrass hay experiment.

Materials and Methods

Site Description

The study was conducted on a 0.53 ha field site from 2003 to 2005 on a 4400-head swine finishing farm in Duplin County, North Carolina (35°05′ N, 78°02′ W). The soil series was an Autryville loamy sand (loamy, siliceous, subactive, thermic Arenic Paleudults). Prior to initiation of the study, the site was a coastal bermudagrass (*Cynodon dactylon* L.) pasture that periodically received overhead irrigation from a swine wastewater lagoon. The site was adjacent to an experimental swine wastewater treatment facility (Vanotti, 2004; Vanotti et al., 2001). Wastewater used in this study had previously been treated (table 1) to reduce the N and P concentrations (Vanotti, 2004).

Irrigation and Control Systems

The study consisted of coastal bermudagrass production as a hay crop with 36 plots (9.6 × 9.6 m) containing nine treatments. The plots were arranged in a randomized complete block design with four replicates (fig. 1). The irrigation treatments consisted of (1) three water application rates (non-irrigated, irrigation applied to meet 100% of evapotranspiration (ET_c), and irrigation applied to meet 75% of ET_c); (2) two SDI lateral spacings (0.6 m and 1.2 m) at a depth of 0.3 m; (3) two nutrient sources (commercial fertilizer and treated swine wastewater); and (4) four replications. The non-irrigated plots received only commercial fertilizer. The SDI laterals were installed 0.3 m below the soil surface using two poly-hose injection shanks mounted on a tool bar. The irrigation system for each plot consisted of individual PVC pipe manifolds for both supply and discharge. Discharge manifolds were flushed back to the adjacent lagoon. Irrigation laterals were WasteflowPC (Geoflow, Inc., Corte Madera, Cal.) with in-line, pressure-compensating labyrinth emitters spaced 0.6 m apart with each delivering 1.9 L h^{-1}. The SDI system was operated at a pressure of approximately 207 kPa.

The SDI irrigation system was controlled by a 200 GHz Pentium PC with a custom Visual Basic (VB) program. The VB program operated a digital output PCI board, an A/D input board, and a counter/timer board. The digital output board operated supply pumps and solenoid valves. The A/D input board read supply line pressures. The counter/timer board recorded flows. Two 22.7 m^3 water storage tanks were used to store well water and wastewater for the irrigation system. Float switches controlled irrigation tank water levels. Each water source had a dedicated pump. Selected treatments could receive treated effluent, and all treatments could receive well water. In-line screen filters were used for both well water and wastewater. Additionally, a media filter with sand and gravel was used to filter the treated effluent before it reached the screen filter. Flowmeters were used on each water source as well as each treatment. Supply pressures were monitored using pressure transducers that were placed before and after the in-line screen filter for each water source.

Weather Station

A tripod-mounted weather station was installed at the irrigation site with a data logger (CR10, Campbell Scientific, Logan, Utah) to measure relative humidity, air temperature, solar radiation, wind speed, wind direction, and rainfall. The data logger tabulated data at 5 min intervals and downloaded daily to the irrigation control PC. Reference crop evapotranspiration (ET_o) was calculated using daily weather station data and the ASCE Standardized reference crop ET equation (Allen et al., 2005). Reference crop evapotranspiration was multiplied by a crop coefficient (Allen et al., 1998) to obtain daily crop ET values (ET_c). The ET_c and daily effective rainfall were accumulated for the previous seven days. Effective rainfall was defined as a rainfall not exceeding 25 mm in a day. When the cumulative ET_c exceeded cumulative effective rainfall by more than 6 mm, an irrigation event was initiated.

Forage Production

Wheat (*Triticum aestivium* L., cv. Southern States FFR535) was planted in the forage plots on 2 December 2003 and 29 November 2004 and was removed before initiation of bermudagrass growth. The target total nitrogen (TN) application rate for the bermudagrass plots was 270 kg ha^{-1} applied in three applications (one application of 90 kg ha^{-1} for each cutting). The non-irrigated treatment received nitrogen through surface application of 34% ammonium nitrate fertilizer in one application per cutting. The commercial fertilizer SDI treatments received one to two applications of 30% UAN per cutting. The wastewater SDI plots received treated effluent from the adjacent treatment plant. An analysis of the treated effluent was used to estimate the quantity of effluent to be applied. During applications, a second sample was collected for analysis to determine actual application amounts. In 2004, the TN concentration was ~465 mg L^{-1}. At this concentration, only one to two applications were required to supply the target application rate. In 2005, the effluent TN concentration was ~94 mg L^{-1}, and four to five applications per cutting were required. Bermudagrass hay was harvested three times in both 2004 (23 June, 10 Aug., and 21 Sept.) and 2005 (12 July, 11 Aug., and 13 Oct.). Hay yields were determined by harvesting 15.4 m^2 (1.6 × 9.6 m) of each plot and weighing the harvested biomass in the field. A sample was collected from each harvested plot, weighed in the laboratory, dried at 43°C for 72 h, and weighed after drying to determine the moisture content of the bermudagrass hay. Yields are reported on a dry weight basis. Plant nitrogen was determined on the dried plant sample with a Leco C/N 2000 analyzer (Leco Corp., St. Joseph, Mich.).

Soil Analysis

Soil samples were collected from each main plot on 13 June 2002, 9 September 2003, 19 October 2004, and 24 January 2006. Fifteen soil cores (15 cm L × 2 cm dia.) were taken at 15 cm increments to a depth of 60 cm. The core samples were composited for each main plot, placed in storage bags, transported to the laboratory, and air-dried for one week. The air dried samples were ground to pass a 2 mm sieve. Soil nitrogen and carbon were determined with a Leco C/N 2000 analyzer.

Soil Water Analysis

Two soil water lysimeters (model 1900, Soilmoisture Equipment Corp., Goleta, Cal.) were installed in the center of each main plot at depths of 30 and 90 cm. A 7.6 cm hole was augured for both lysimeters to a depth of 30 cm and 91 cm. Silica flour was poured into the bottom of the hole, and the soil water lysimeters (4.8 cm dia.) was inserted into the hole. Soil excavated from the hole was used to pack around the lysimeters. Soil water samples were collected by placing a vacuum (400 kPa) on the lysimeters for 12 h and pumping the sample from the lysimeter on the following day. Samples were collected on eleven dates (20 April 2004, 12 May 2004, 23 June 2004, 18 Aug. 2004, 23 Sept. 2004, 14 Oct. 2004, 30 Nov. 2004, 9 March 2005, 9 June 2005, 16 Aug. 2005, and 13 Oct. 2005). The samples were placed in glass bottles, packed on ice, and transported to the laboratory. In the laboratory, they were stored at 4°C until they were analyzed.

Soil water samples were analyzed for pH, redox potential, and conductivity with a Thermo Orion (Thermo Electron Corp., Waltham, Mass.) model 420A$^+$ meter, model 250 meter, and model 115A$^+$ meter, respectively, within 48 h of collection. Following pH measurements, the soil water samples were acidified with H_2SO_4 to a pH <2. The acidified water samples were analyzed for nitrate-N, ammonia-N, dissolved orthophosphate, and chloride on a Bran+Luebbe Auto-Analyzer (Bran+Luebbe Corp., Hamburg, Germany) using EPA methods 353.1, 350.1, 365.1, and 325.1, respectively (Kopp and McKee, 1983).

The experimental design was a randomized complete block design. The plots were combinations for irrigation (lateral spacing and irrigation applications) and nutrient application (commercial and treated wastewater). Data were analyzed by Proc GLM (general linear model) and LSD (least significant difference) with SAS Version 9.1 (SAS Institute Inc., Cary, N.C.). Significant differences for main plot and subplots, and interactions were based on F-tests ($P > 0.05$).

Results

Hay Yields

In 2004, bermudagrass hay yields ranged from 5.65 to 10.31 Mg ha^{-1}; however, in 2005, yields were much higher, ranging from 10.97 to 14.08 Mg ha^{-1} (table 2). The 2004 yields were comparable to the county average of 7.08 Mg ha^{-1}, while the 2005 yields were almost double the county average of 6.77 Mg ha^{-1} (USDA-NASS, 2006). Because of the large differences between the yields, the data were analyzed for significant differences for each year.

Lower yields in 2004 appear to have been caused by multiple factors. The total growing period for 2004 was approximately 32 days shorter than in 2005. The total growing period

Table 2. Bermudagrass hay yields at the subsurface drip irrigation study site (based on plot harvest).

SDI Spacing	Fertilizer	Irrigation Rate	Yield[a] (Mg ha^{-1}, dry weight) 2004	2005
0.6 m	Commercial	100%	6.70 ±0.43	12.68 ±1.57
		75%	7.50 ±0.61	12.93 ±1.26
	Effluent	100%	7.99 ±2.19	12.24 ±3.69
		75%	7.98 ±0.18	14.08 ±1.30
1.2 m	Commercial	100%	5.65 ±1.64	10.97 ±2.90
		75%	7.20 ±1.84	11.04 ±4.16
	Effluent	100%	8.58 ±1.71	13.21 ±3.34
		75%	10.31 ±1.05	13.64 ±1.04
Non-Irrigated			8.13 ±0.69	12.26 ±3.12
		$LSD_{0.05}$	1.76	3.92
Summary Statistics for SDI Irrigated Plots (means)[b]				
	Spacing	0.6 m	7.54 a	12.98 a
		1.2 m	7.93 a	12.22 a
	Fertilizer	Commercial	6.76 a	11.91 a
		Effluent	8.71 b	13.29 a
	Irrigation Rate	100%	7.23 a	12.28 a
		75%	8.25 a	12.92 a

[a] 2004 and 2005 average total hay production for Duplin County, N.C., was 7.08 and 6.77 Mg ha^{-1}, respectively (USDA-NASS, 2006).

[b] Means followed by the same letter are not significantly different at the P = 0.05 level.

as we defined it was the period between when the winter wheat crop was removed and the final hay harvested. In both years, the start of the growing period was reduced from normal practices to allow for removal of the winter wheat cover crop. In 2004, the wheat cover crop was removed on 27 May, and the final harvest was on 21 September. In 2005, the wheat cover crop was removed on 17 May, and the final harvest was on 13 October. Each year there were three hay cuttings. In 2004, the hay cuttings were at approximately 4-, 6-, and 6-week intervals. In 2005, the hay cuttings were at approximately 8-, 4-, and 8-week intervals. An additional factor was an extended period between 30 June and 23 July in 2004 with no measurable rainfall.

The measured rainfalls for the 2004 and 2005 growing periods with the on-site weather station were 468 and 385 mm, respectively (table 3). The long-term rainfall averages for the corresponding growing periods were 529 and 634 mm, respectively (Warsaw, N.C.; State Climate Office of North Carolina, 2006). The measured rainfall totals were 88% and 61% of the long-term averages. Long-term average annual rainfall for the weather station at Warsaw, N.C., was 1232 mm (State Climate Office of North Carolina, 2006). The on-site measured rainfalls for 2004 and 2005 were 1244 and 1074 mm, respectively.

Irrigation Application Rates

For 2004 and 2005, the ET_c was 433.1 and 569.7 mm, respectively (table 3). The ET_c, cumulative water applied (irrigation + effective rainfall), and effective rainfall for 2004 and 2005 are shown in table 3 and figures 2 and 3. For both years, our cumulative 100% ET_c application rate treatments exceeded measured ET_c due to interactions with rainfall and as a byproduct of our weekly rainfall and ET_c accumulations. In 2004, the cumulative applications rates for the 75% ET_c treatments were approximately 98% of the 100% ET_c treatment for the commercial fertilizer treatments and approximately 88% for the effluent treatments. These higher cumulative irrigation application rates in 2004 were due to some equipment malfunctions at the initiation of the experiment. In 2005, all 75% ET_c treatments received approximately 88% of the 100% ET_c treatment.

In 2004, the ET_c requirements were met or exceeded during the beginning and end of the growing season. During the mid-portion of the growing season, there was an extended period with no rainfall (~23 days) that resulted in less applied irrigation than the ET_c requirements. The total irrigation water applied for 2004 was 95 to 158 mm for the ET_c treatments. In 2005, although there was less total rainfall than in 2004, water was applied fairly close to the ET_c requirements throughout the season. The total irrigation water applied for 2005 was 284.5 and 362.7 mm for the 75% and 100% ET_c treatments, respectively.

For both years, we compared the non-irrigated treatment to the two irrigation treatments (75% and 100% ET_c). There were no significant differences in bermudagrass hay yields between the non-irrigated and irrigation treatments. For both 2004 and 2005, there was no statistical difference in the bermudagrass hay yields between the two irrigation treatments (table 2). These results indicate that the lower irrigation rate

Table 3. Irrigation and wastewater effluent application depths for the SDI irrigation system.

SDI Spacing	Fertilizer	Irrigation Rate	2004 Applications (mm) Well Water	Effluent	Total Irrigation	Total Water Applied	2005 Applications (mm) Well Water	Effluent	Total Irrigation	Total Water Applied
0.6 m	Commercial	100%	108.2	--	108.2	505.2	362.7	--	362.7	697.2
		75%	100.6	--	100.6	497.6	284.5	--	284.5	619.0
	Effluent	100%	96.8	61.2	158.0	555.0	115.1	247.7	362.7	697.2
		75%	33.8	61.2	95.0	492.0	36.8	247.7	284.5	619.0
1.2 m	Commercial	100%	108.2	--	108.2	505.2	362.7	--	362.7	697.2
		75%	100.6	--	100.6	497.6	284.5	--	284.5	619.0
	Effluent	100%	96.8	61.2	158.0	555.0	115.1	247.7	362.7	697.2
		75%	33.8	61.2	95.0	492.0	36.8	247.7	284.5	619.0
Non-Irrigated[a]						397.0				334.5
ET_c						433.1				569.7
Rainfall						467.6				385.1

[a] Non-irrigated total water applied is defined as the effective rainfall. Effective rainfall was added to total irrigation to determine total water applied for the irrigated treatments.

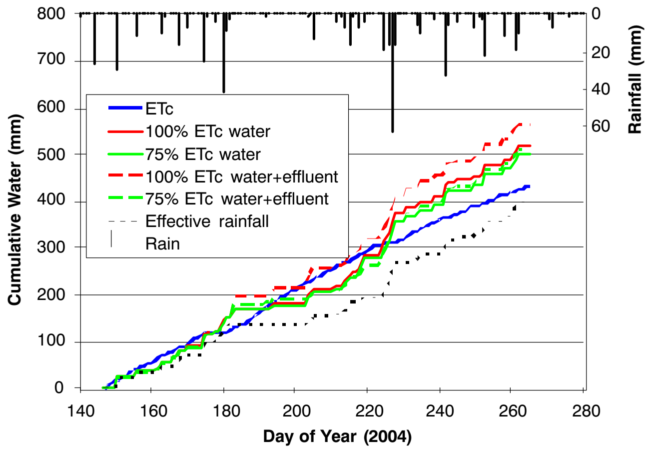

Figure 2. Cumulative water (effective rainfall, evapotranspiration, and irrigation) for the 2004 subsurface drip irrigated bermudagrass hay.

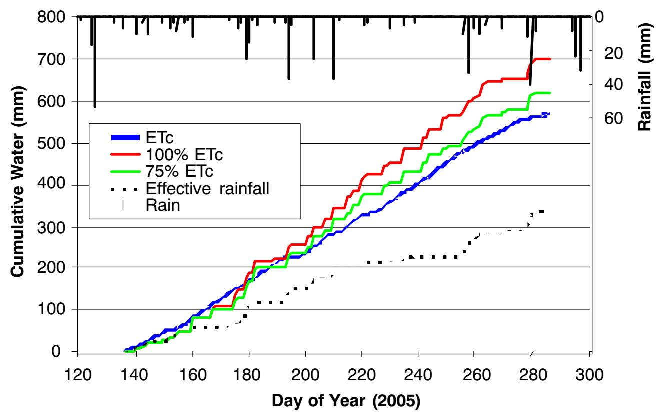

Figure 3. Cumulative water (effective rainfall, evapotranspiration, and irrigation) for the 2005 subsurface drip irrigated bermudagrass hay. Total water applied for the commercial and wastewater effluent treatments were equal in 2005.

(75% ET_c) could be utilized to reduce water usage and to reduce the potential for leaching nutrients below the root zone without reducing bermudagrass hay yields.

SDI Lateral Spacing

The lateral drip tube spacing had no significant effect on bermudagrass hay yields in either 2004 or 2005 (table 2). In 2004, mean hay yields for the 0.6 and 1.2 m lateral spacing were 7.94 and 7.54 Mg ha^{-1}, respectively. In 2005, mean hay yields for the 0.6 and 1.2 m lateral spacing were 12.98 and 12.22 Mg ha^{-1}, respectively. The use of the wider lateral spacing could result in significant savings in irrigation installation cost. Camp et al. (1997) reported an approximate 30% cost savings using wider lateral spacing for a cotton row crop. Wider lateral spacing than used in this study may further increase savings; however, the risk of reduced yields in years with extreme drought would have to be taken into consideration over the long term. For both lateral spacings, we observed uneven bermudagrass growth. The uneven growth was more noticeable in the wider 1.2 m spacing treatments. We attributed the uneven growth to uneven lateral water and nutrient movement away from the SDI laterals in the coarse soil. Camp et al. (1997) observed uneven row crop growth during drought conditions. In an adjacent SDI row crop experiment (unpublished data), we observed low yields and similar uneven row crop growth.

Fertilizer Source (Commercial or Effluent)

Wastewater effluent or commercial fertilizer was applied to the bermudagrass hay plots. In 2005, there were no significant differences in hay yield for either fertilizer (table 2). In 2004, the effluent treatments produced significantly higher yields than those with commercial fertilizer. There was also a significant interaction between the fertilizer source and the SDI lateral spacing. The nutrient application rate in 2004 was approximately 280 kg N ha^{-1} for all treatments. In 2004, the wastewater effluent TN concentration was 465 mg L^{-1} and was applied through the SDI system in one to two applications. In 2005, the nutrient application rates were 303 kg N ha^{-1} for the commercial fertilizer plots and 233 kg N ha^{-1} for the wastewater effluent treatment plots. In 2005, the wastewater effluent TN concentration was much lower, averaging 94 mg L^{-1}, and required multiple injections to reach the target application rate. The commercial fertilizer was applied in one or two injections. In both years, to keep the total water applications for all irrigation treatments approximately equal, additional irrigation (well water only) was required for the commercial fertilizer plots. In 2005, this additional water could have potentially moved the applied commercial fertilizer deeper in the soil profile and adversely affected hay yields.

Hay Nitrogen Removal

From the harvested hay, we determined N removal via plant uptake from the different treatments (table 4). The bermudagrass hay plant nitrogen concentration was not significantly different for any of the treatments. Mean plant nitrogen concentration ranged from 1.93% to 2.25%. Burns et al. (1985) found plant N concentration from 2.2% to 2.9% in sprinkler-irrigated bermudagrass with lagoon effluent at application rates ranging from 338 to 1340 kg ha^{-1}.

The mass N removed by the bermudagrass hay ranged from 120 to 261 kg ha^{-1} over the two-year project. The mass nitrogen in the bermudagrass hay was not significant for any treatments, with the exception of the 2004 fertilizer treatments. The 2004 SDI treatments with wastewater effluent had significantly higher plant nitrogen in the hay biomass than the treatments with commercial fertilizers. Adeli et al. (2003) reported similar N removal rates ranging from 265 to 302 kg ha^{-1} from bermudagrass irrigated with swine lagoon effluent at loading rates from 200 to 600 kg ha^{-1}. Burns et al. (1985) reported N removal rates of 247 to 450 kg ha^{-1} from lagoon effluent-irrigated bermudagrass with application rates ranging from 338 to 1340 kg ha^{-1}. Our N loading rates ranged from 233 to 300 kg ha^{-1} over the two-year study, and our N uptake rates compared favorably with the lower N loading in similar studies.

Soil Nitrogen and Carbon

Soil N and C data from samplings before, during, and at the conclusion of the study are shown in table 5. The soil N and C values were not significantly different for any treatments. The soil C values for the surface layers ranged from 5483 to 7434 mg kg^{-1}, which were within the expected range for these soils. Novak et al. (2007) reported similar soil C values for the 0 to 5 cm layer (6300 to 9200 mg kg^{-1} for conventional tillage and 5300 to 15900 mg kg^{-1} for conservation tillage systems). For each year of the study, soil N values were not significantly different across treatments.

Table 4. Plant nitrogen in bermudagrass hay from the subsurface drip irrigation study.

SDI Spacing	Fertilizer	Irrigation Rate	Plant Nitrogen (%) 2004	Plant Nitrogen (%) 2005	Plant Nitrogen ($kg\ ha^{-1}$) 2004	Plant Nitrogen ($kg\ ha^{-1}$) 2005
0.6 m	Commercial	100%	2.05 ±0.06	1.94 ±0.10	138.0 ±10.37	238.8 ±34.40
		75%	2.12 ±0.10	1.96 ±0.06	158.9 ±11.41	247.7 ±19.89
	Effluent	100%	2.25 ±0.20	2.02 ±0.19	177.1 ±38.84	239.3 ±64.66
		75%	2.17 ±0.05	1.94 ±0.11	172.8 ±8.03	261.3 ±36.62
1.2 m	Commercial	100%	2.14 ±0.11	2.04 ±0.13	120.0 ±32.36	214.8 ±52.36
		75%	2.04 ±0.06	1.95 ±0.08	147.3 ±37.43	213.4 ±85.10
	Effluent	100%	2.21 ±0.13	1.99 ±0.11	188.1 ±30.99	254.7 ±65.72
		75%	2.10 ±0.04	1.93 ±0.04	215.0 ±20.05	257.6 ±22.58
Non-Irrigated	Commercial		2.23 ±0.06	2.06 ±0.16	180.3 ±12.74	239.3 ±68.94
		$LSD_{0.05}$	0.12	0.07	36.1	60.8
Summary Statistics for SDI Irrigated Plots (means)[a]						
	Spacing	0.6	2.16 a	1.96 a	161.7 a	246.8 a
		1.2	2.12 a	1.98 a	167.6 a	235.1 a
	Fertilizer	Commercial	2.09 a	1.97 a	141.1 a	228.7 a
		Effluent	2.18 a	1.97 a	188.2 b	253.2 a
	Irrigation Rate	100%	2.16 a	2.00 a	155.8 a	236.9 a
		75%	2.11 a	1.95 a	173.5 a	245.0a

[a] Means followed by the same letter are not significantly different at the P = 0.05 level.

Table 5. Soil nitrogen and carbon in Bermuda grass plots at subsurface irrigation study.[a]

	Soil Depth (cm) 0-15	15-30	30-45	45-60
Soil Nitrogen ($mg\ kg^{-1}$)				
2003	432 ±66 b	266 ±337 a	139 ±41 b	100 ±59 b
2004	574 ±113 a	290 ±57 a	236 ±55 a	205 ±70 a
2006	480 ±317 b	344 ±385 a	220 ±107 a	206 ±159 a
Soil Carbon ($mg\ kg^{-1}$)				
2003	6456 ±1112 a	4234 ±964 a	3116 ±801 a	2359 ±885 a
2004	7434 ±1775 b	4445 ±1181 a	3125 ±776 a	2269 ±583 a
2006	5483 ±1019 c	2934 ±794 b	2080 ±668 b	1555 ±442 b

[a] Means followed by the same letter are not significantly different at the P = 0.05 level.

Soil Water Analysis

Soil water pH and Eh were consistent throughout the study and were not significantly different across the treatments (table 6). At the 30 cm depth, the ammonia-N concentrations were significantly higher for the effluent applications and the Cl concentrations were significantly different for the spacing and fertilizer treatments. At the 90 cm depth, the conductivity, nitrate-N, and Cl were significantly higher for the effluent applications. Overall, the ammonia-N concentrations in the lysimeter samples were low across the treatments and depths. The effluent N was mainly applied in the nitrate-N form. The soil water nitrate-N concentrations ranged from 1.76 to 6.43 $mg\ L^{-1}$ in the 30 cm lysimeters and from 2.95 to 17.77 $mg\ L^{-1}$ in the 90 cm lysimeters, indicating the potential for leaching. These nitrate-N concentration values were similar to shallow groundwater nitrate-N concentration reported by Stone et al. (1998) in the adjacent watershed on intensively managed agricultural fields. Figures 4 and 5 show soil water TN concentrations over the duration of the project. For the 90 cm depth lysimeter, the TN concentrations fluctuated throughout the study, and TN was generally higher with the

Table 6. Soil water nutrient data from lysimeters in subsurface drip irrigation bermudagrass plots.[a]

Depth			pH	Eh (mV)	Conductivity ($\mu S\ cm^{-1}$)	NO_3-N ($mg\ L^{-1}$)	NH_4-N ($mg\ L^{-1}$)	Ortho-P ($mg\ L^{-1}$)	Cl ($mg\ L^{-1}$)
30 cm	Spacing	0.6 m	6.2 ±0.2	412.0 ±28.2	257.5 ±85.7	4.4 ±2.1	0.2 ±0.1	0.3 ±0.2	11.5 ±11.5*
		1.2 m	6.1 ±0.2	431.0 ±20.1	258.9 ±91.9	4.4 ±4.6	0.2 ±0.1	0.4 ±0.3	6.2 ±4.8*
	Fertilizer	Commercial	6.1 ±0.1	425.7 ±25.2	238.7 ±74.0	4.7 ±4.5	0.1 ±0.0*	0.4 ±0.3	3.6 ±2.3*
		Effluent	6.2 ±0.3	416.4 ±27.0	279.0 ±97.8	4.1 ±2.3	0.2 ±0.1*	0.4 ±0.3	14.1 ±10.3*
	Irrigation Rate	100%	6.2 ±0.2	420.9 ±23.3	257.6 ±95.8	5.5 ±4.2	0.2 ±0.1	0.3 ±0.3	10.1 ±9.1
		75%	6.1 ±0.3	421.5 ±30.1	258.8 ±79.1	3.3 ±2.2	0.1 ±0.1	0.4 ±0.3	7.6 ±9.1
	Non-Irrigated		5.9 ±0.6	421.8 ±28.6	312.0 ±208.9	2.9 ±2.2	0.2 ±0.1	0.3 ±0.3	4.0 ±2.8
90 cm	Spacing	0.6 m	5.8 ±0.2*	420.7 ±20.8	360.3 ±182.8	13.2 ±7.4	0.1 ±0.1	0.2 ±0.2	28.7 ±30.5
		1.2 m	5.9 ±0.1*	425.4 ±20.8	268.3 ±91.3	10.8 ±6.5	0.1 ±0.0	0.2 ±0.1	25.4 ±26.6
	Fertilizer	Commercial	5.9 ±0.1	432.0 ±20.7	230.9 ±71.9*	9.8 ±6.3*	0.1 ±0.1	0.1 ±0.1	6.3 ±8.6*
		Effluent	5.9 ±0.2	414.1 ±16.7	397.7 ±162.1*	14.2 ±7.1*	0.1 ±0.1	0.2 ±0.2	47.8 ±25.5*
	Irrigation Rate	100%	5.8 ±0.2	428.7 ±15.9	355.7 ±178.7	14.3 ±7.3	0.1 ±0.1	0.2 ±0.1	32.2 ±31.5
		75%	5.9 ±0.2	417.4 ±23.6	272.9 ±103.4	9.7 ±6.0	0.1 ±0.1	0.2 ±0.2	21.9 ±24.3
	Non-Irrigated		5.9 ±0.2	433.1 ±26.1	305.5 ±83.3	4.6 ±4.0	0.1 ±0.0	0.1 ±0.0	19.8 ±9.8

[a] Means followed by an asterisk (*) are significantly different at the P = 0.05 level.

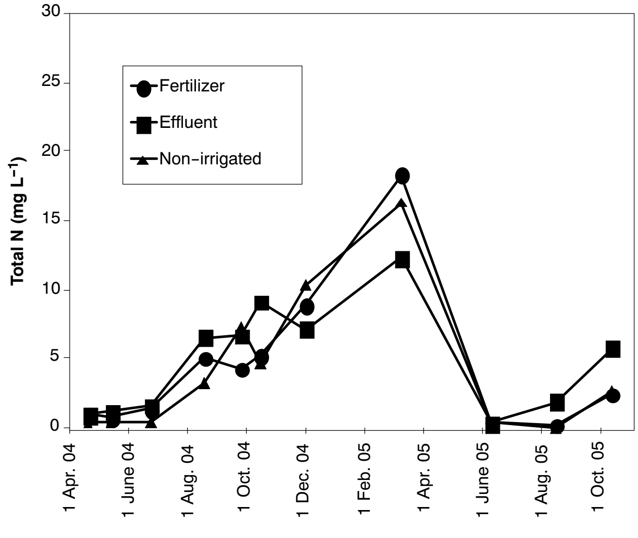

Figure 4. Total nitrogen in soil water at 30 cm in the subsurface drip irrigated bermudagrass hay plots.

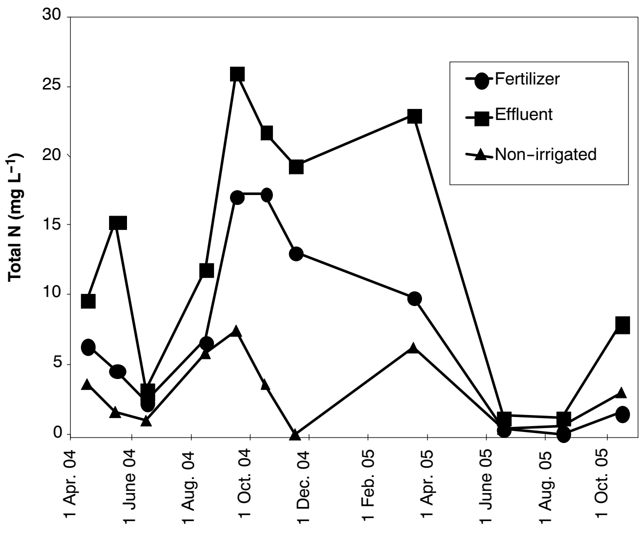

Figure 5. Total nitrogen in soil water at 90 cm in the subsurface drip irrigated bermudagrass hay plots.

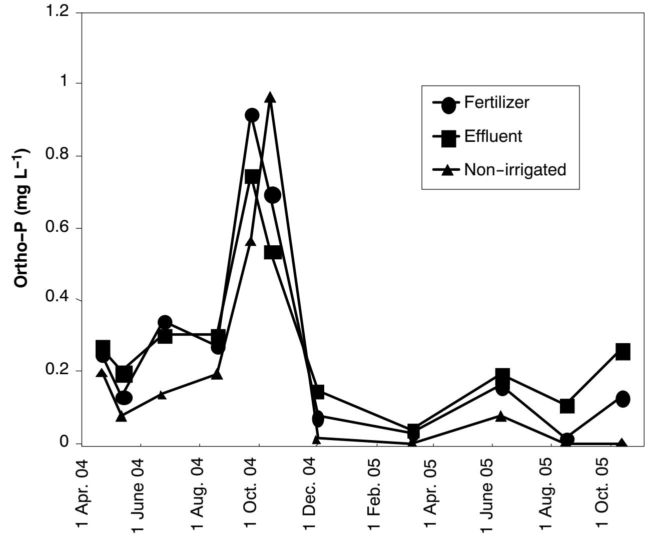

Figure 6. Ortho-phosphorus in soil water at 30 cm in the subsurface drip irrigated bermudagrass hay plots.

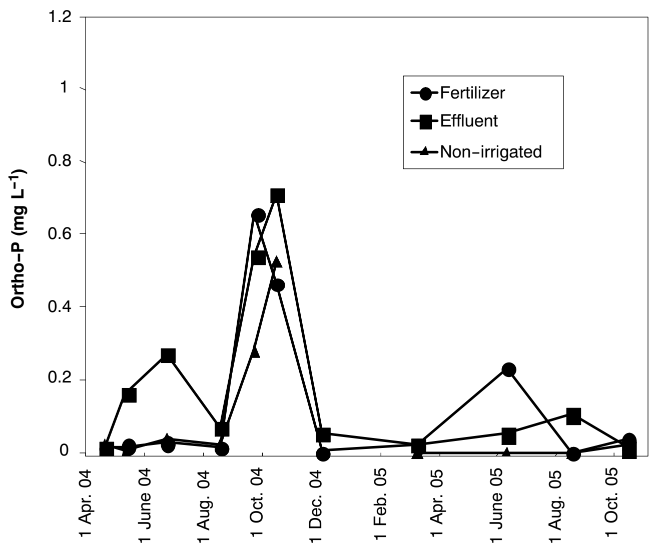

Figure 7. Ortho-phosphorus in soil water at 90 cm in the subsurface drip irrigated bermudagrass hay plots.

effluent treatments. The highest level of TN in the 30 cm lysimeter occurred between the end of the 2004 season and the spring of 2005, before the start of the season. These lysimeter TN results indicate that winter and spring rainfalls influenced the TN concentrations.

The ortho-phosphorus (ortho-P) concentrations were not significant for any treatment or depth. The mean ortho-P concentrations ranged from 0.2 to 0.45 mg L^{-1} in the 30 cm lysimeters and 0.07 to 0.31 mg L^{-1} in the 90 cm lysimeters. These concentrations at the two depths do not indicate any leaching of ortho-P through the soil profile. In this study, the only treatments that received any P were the effluent treatments. These effluent treatments received 6.8 and 37 kg ha^{-1} for 2004 and 2005, respectively. The soil water ortho-P concentrations were probably influenced by prior operation of the field before the project began. The ortho-P concentrations for the project duration are shown in figures 6 and 7. The temporary increases in ortho-P concentration followed a large rainfall period in 2004.

Summary and Conclusions

The subsurface drip irrigation system was successfully installed and utilized to apply both commercial fertilizer and treated swine wastewater effluent for bermudagrass hay production. The bermudagrass hay production from the SDI system exceeded the county averages for both years of the study. Bermudagrass hay production using the SDI system was not significantly different from non-irrigated control plots.

The bermudagrass hay crop was irrigated at target application rates of either 75% or 100% of the calculated crop evapotranspiration requirements. There were no significant differences in either irrigation application rate across the other treatments. Two SDI lateral spacings were compared with both well water and effluent irrigated bermudagrass hay. There were no significant differences between the two SDI lateral spacings across the other treatments. These results indicate that the use of wider SDI lateral spacing could reduce system cost and increase the economic returns of the SDI system.

The bermudagrass hay crop was fertilized using commercial and treated swine wastewater effluent injected through the SDI system. In 2004, the bermudagrass hay plots receiving swine wastewater effluent had significantly higher yields. The 2005 bermudagrass hay yields were not significantly different for fertilizer source. The 2004 bermudagrass hay plots receiving effluent also had significantly higher plant nitrogen removal than the treatments with commercial fertilizer. These nitrogen removals in plant biomass were similar to those from systems applying much higher rates of swine lagoon effluent.

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